Today's program

0. Summary from last week

Hall effect

Semiconductors vs semimetals & metals

1. Semiconductors

Carrier density

n- and p-type semiconductors

2. Magnetism

Ferromagnetism

Anti-ferromagnetism

Exercise: Magneto-resistance

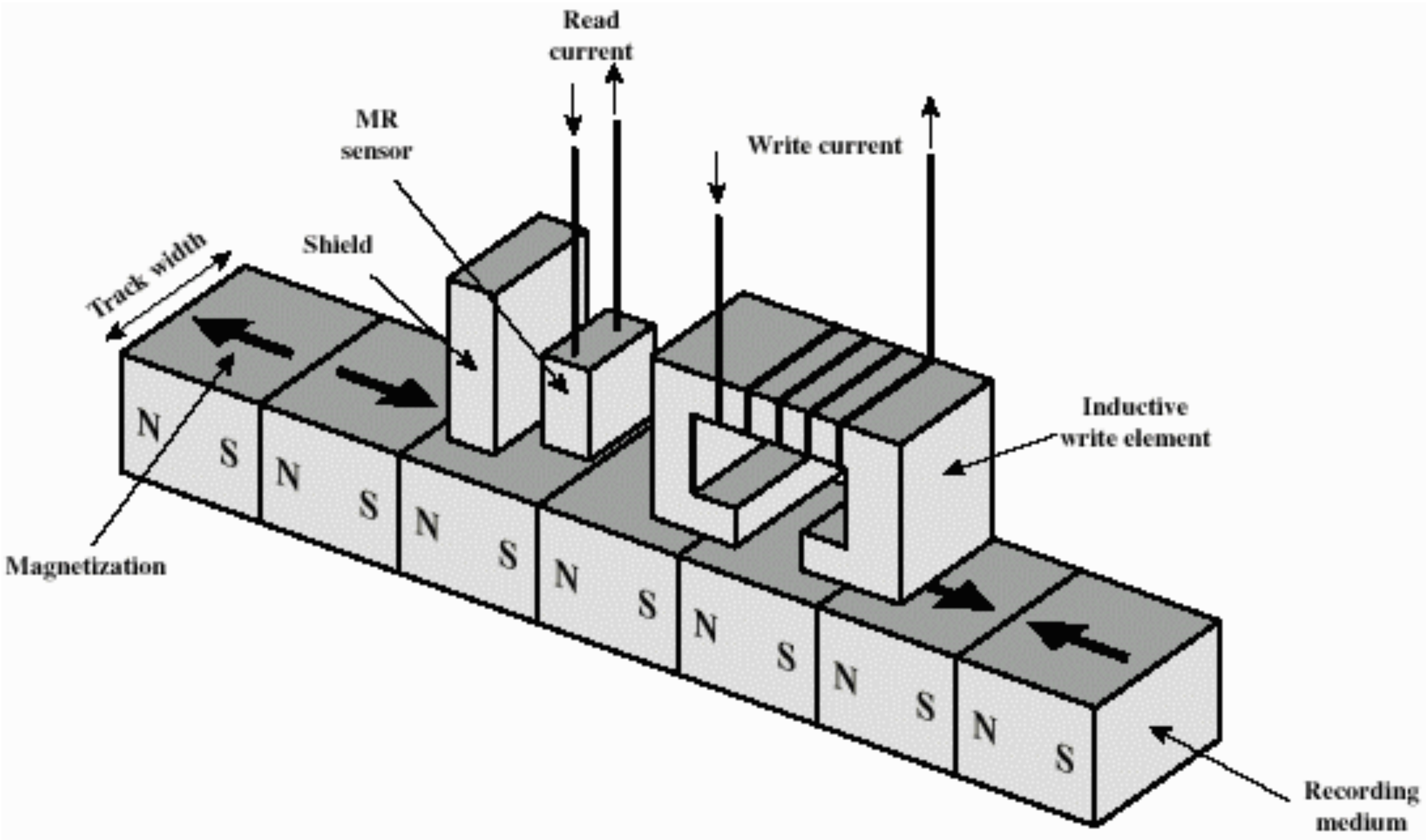
Exercise 2 *Hall effect: Multiband scenario*

In the lecture we derived single-band expressions for the resistivity $\rho = m/ne^2\tau$ and the Hall coefficient $R_\mathrm{H} = -1/ne$. It is convenient to write the relation between the current density $\mathbf{j}$ and the electric field $\mathbf{E}$ as $\mathbf{E} = \boldsymbol{\rho}\mathbf{j}$ where:

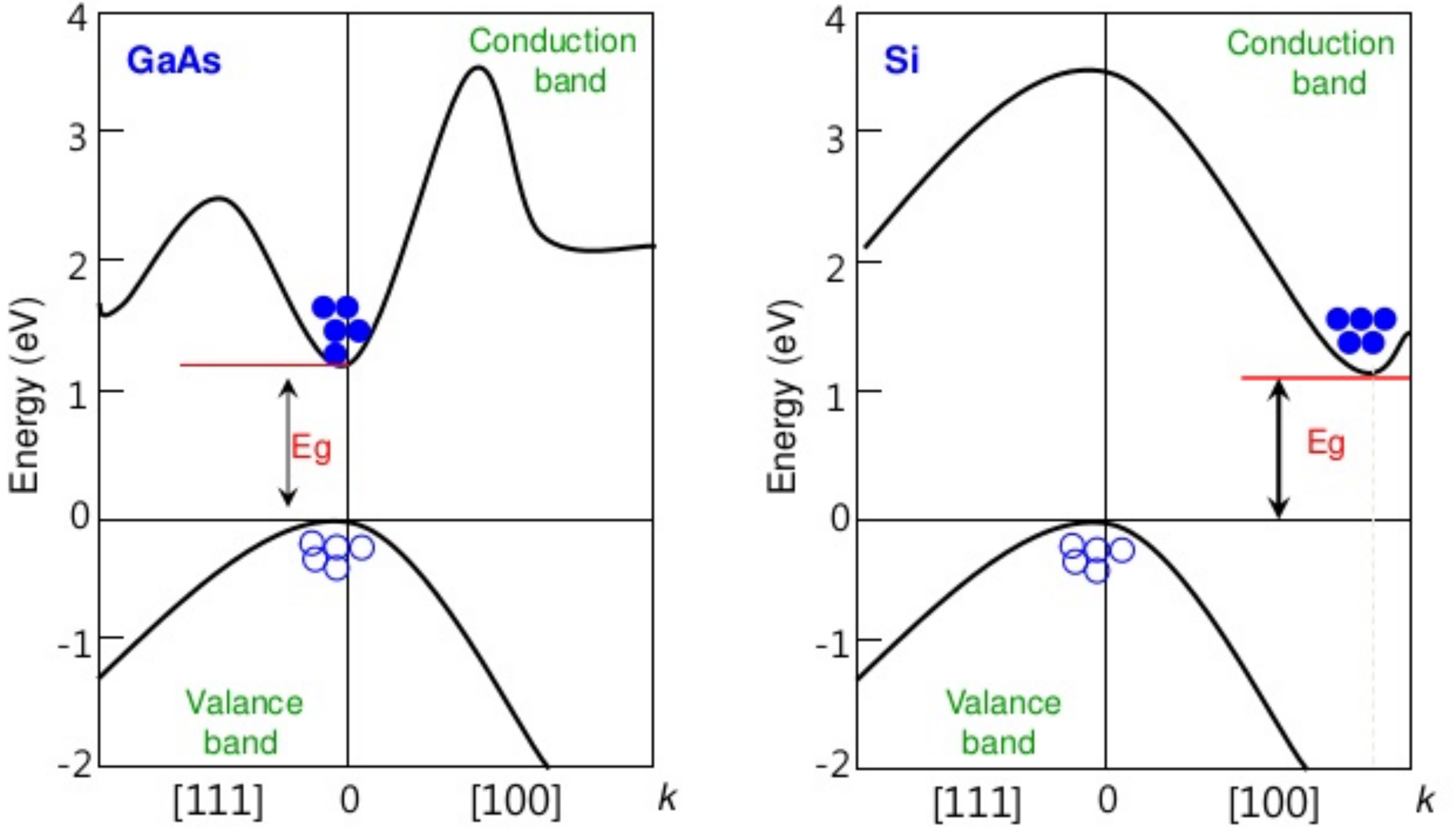
$$\boldsymbol{\rho} = \begin{pmatrix} \rho & -R_\mathrm{H}B \\ R_\mathrm{H}B & \rho \end{pmatrix} \tag{1}$$

Magneto-resistance

The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg "for the discovery of Giant Magnetoresistance"



Band Structure of Semiconductors



Energy band structures of *GaAs* and *Si*

Electronic masses

Crystal	Electron m_e/m
InSb	0.015
InAs	0.026
InP	0.073
GaSb	0.047
GaAs	0.066
Cu_2O	0.99

Better notation:
m_0 = free electron mass
m_e = crystal electron mass
m_h = crystal electron mass

Text added after the lecture.

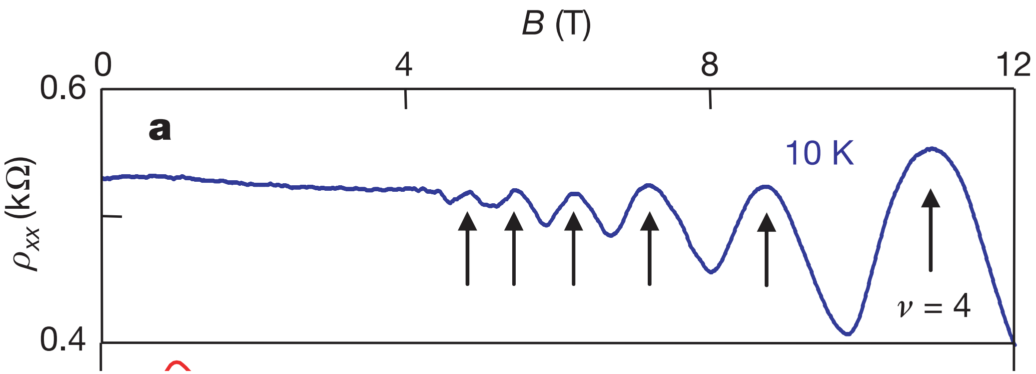
Reading Kittel more careful, it seems that following notation is adopted.
m = is the free electron mass.
m_e = effective crystal electron mass

The fact that the electron mass is lighter in semiconductors is confirmed on the following link.

https://www.youtube.com/watch?v=cdirek91Hto
http://ecee.colorado.edu/~bart/book/effmass.htm

Two-dimensional gas of massless Dirac fermions in graphene

Novoselov & Geim *et al.*, Nature 438, 197 (2005)
Nobel Prize 2010



OSCILLATION AMPLITUDE

$$\propto e^{\left(\frac{-\pi\hbar k_F}{eB\ell}\right)}$$

Quantum Oscillations can give in formation about electronic mass.

Thermal Condition:

$$\hbar\omega_c > k_B T \quad \text{with} \quad \omega_c = \frac{eB}{m}$$

Landau level splitting > thermal energy

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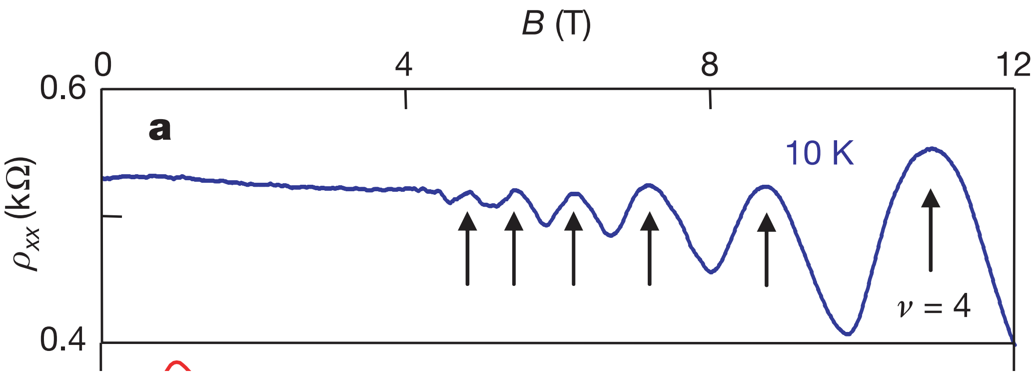

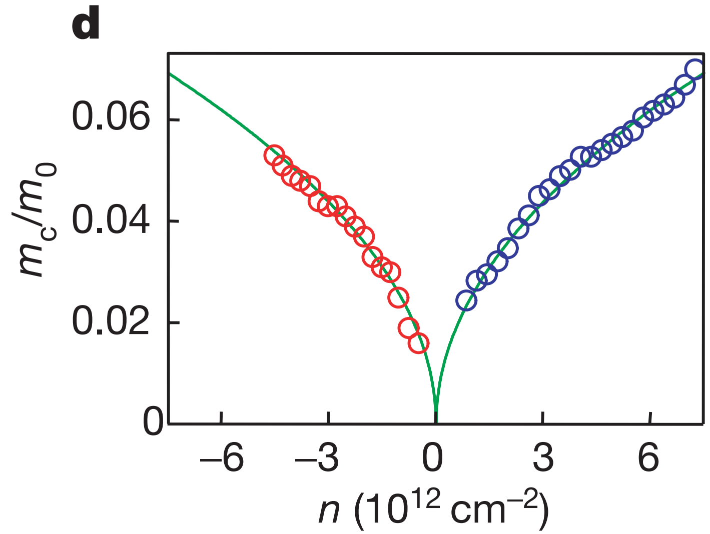

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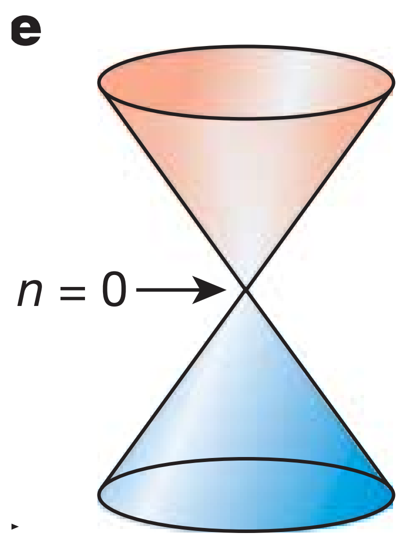
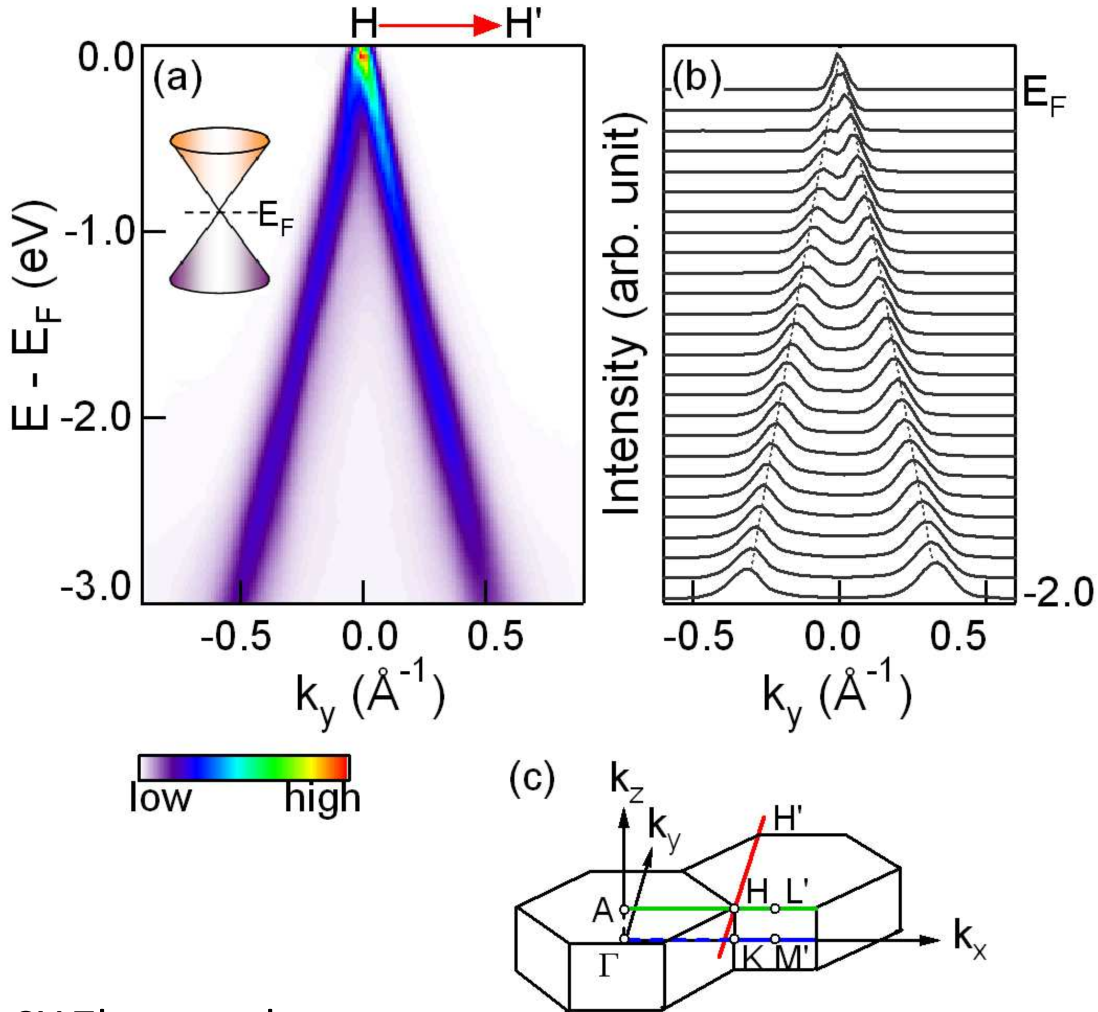


Massless Dirac fermions:

Angle-resolved photoemission spectroscopy



SY Zhou et al.,

Nature Physics 2, **595** - 599 (**2006**)

Conduction Electron Concentration

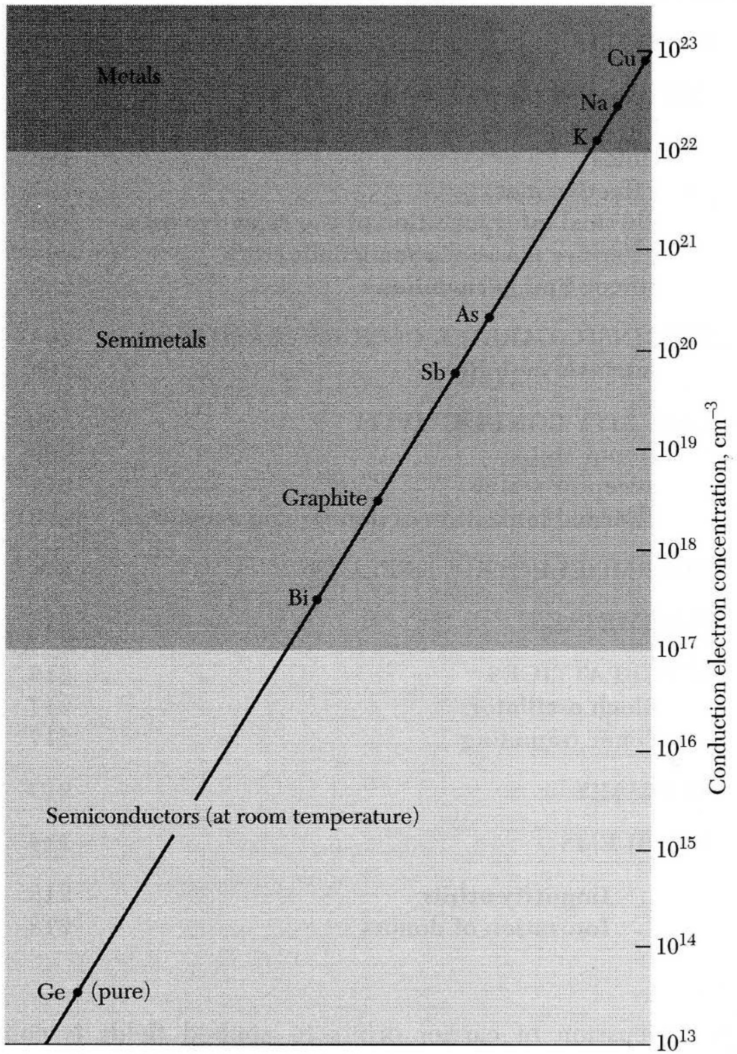
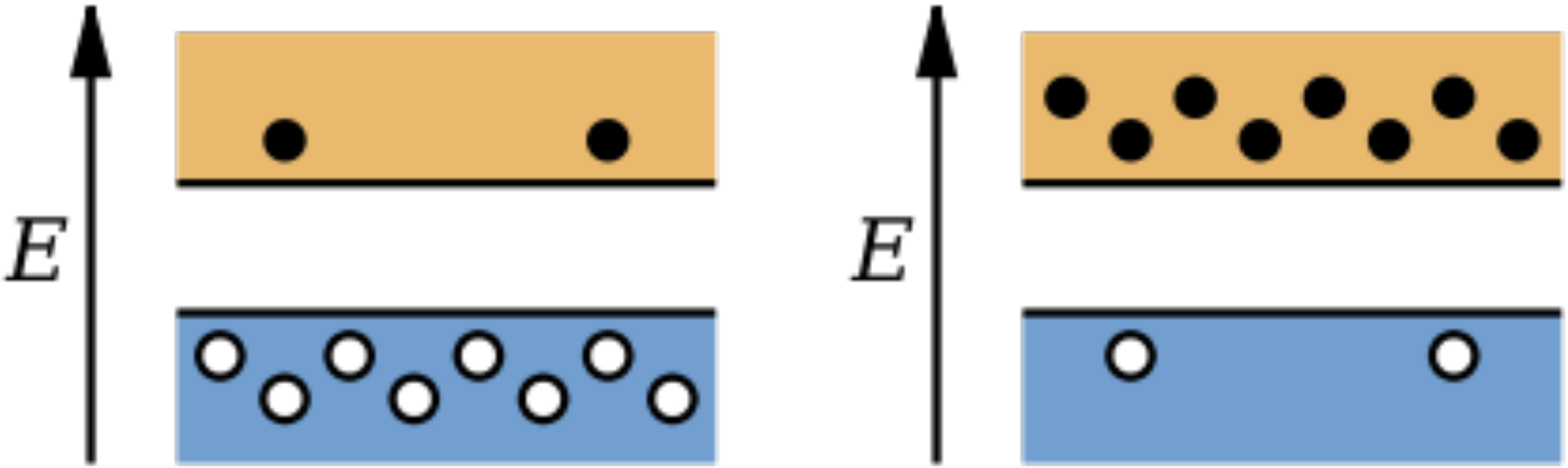


Figure 1 Carrier concentrations for metals, semimetals, and semiconductors. The semiconductor range may be extended upward by increasing the impurity concentration, and the range can be extended downward to merge eventually with the insulator range.

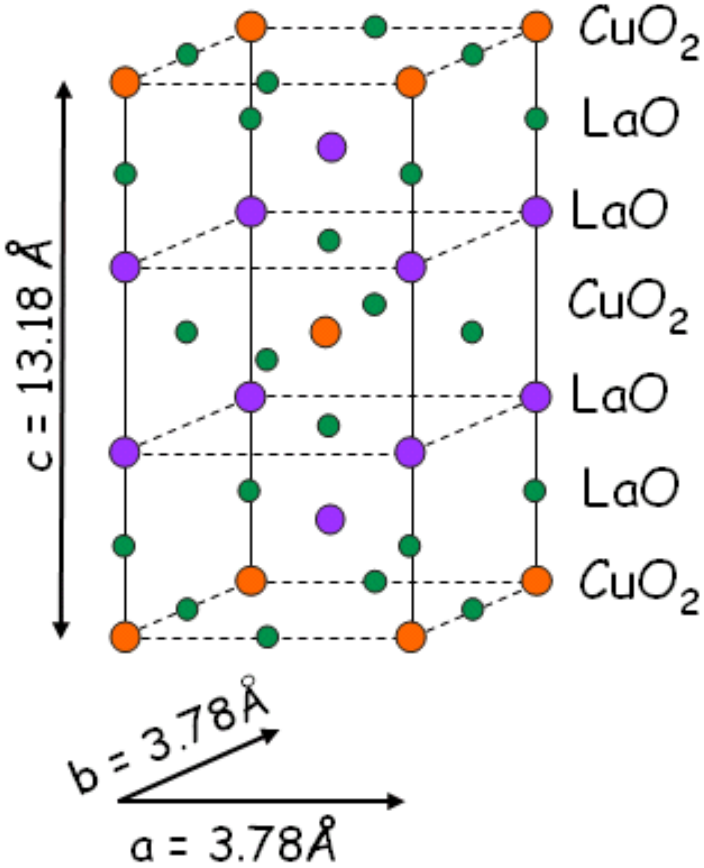
n- and p-type semiconductors



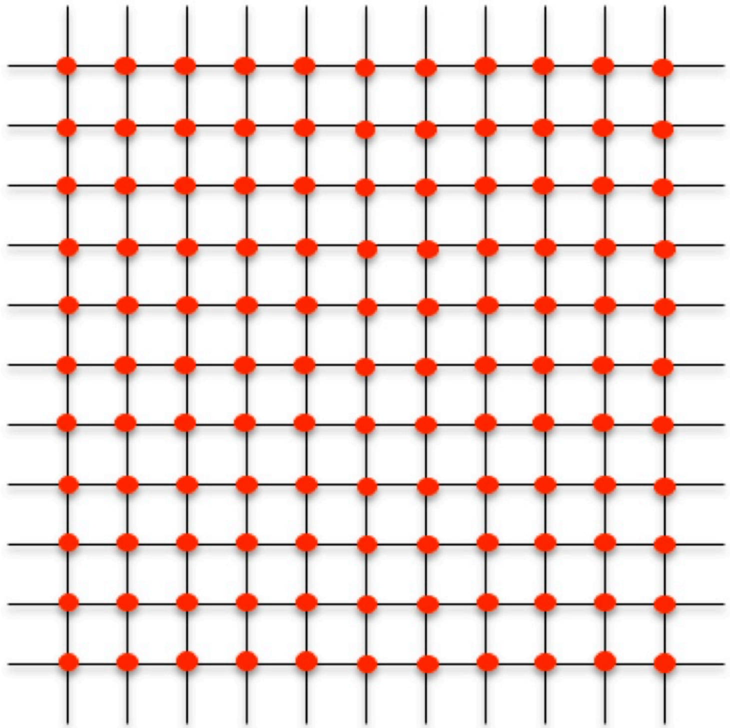
Doping – Performance Enhancement

Doping of materials

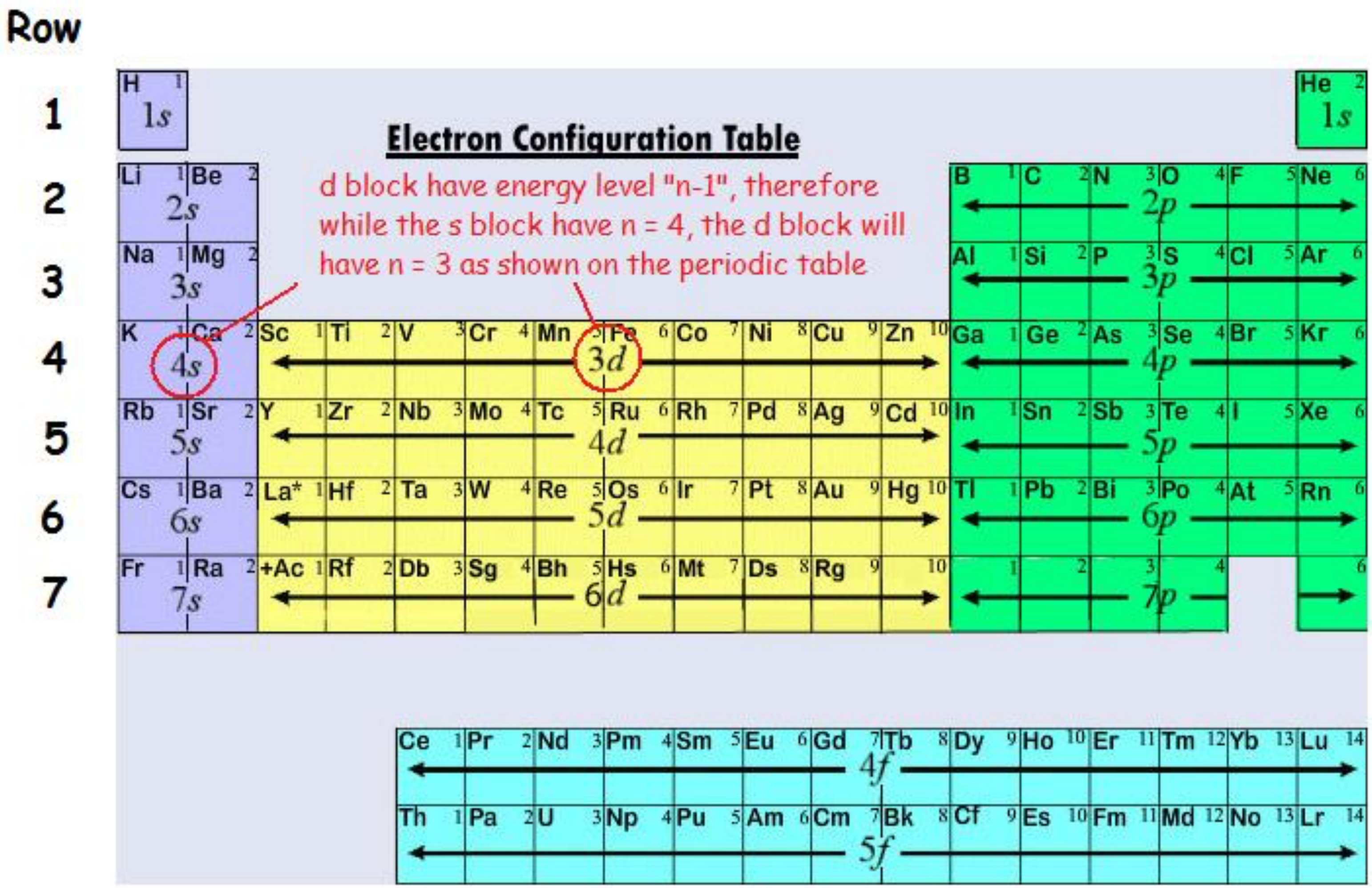
Example: La_2CuO_4



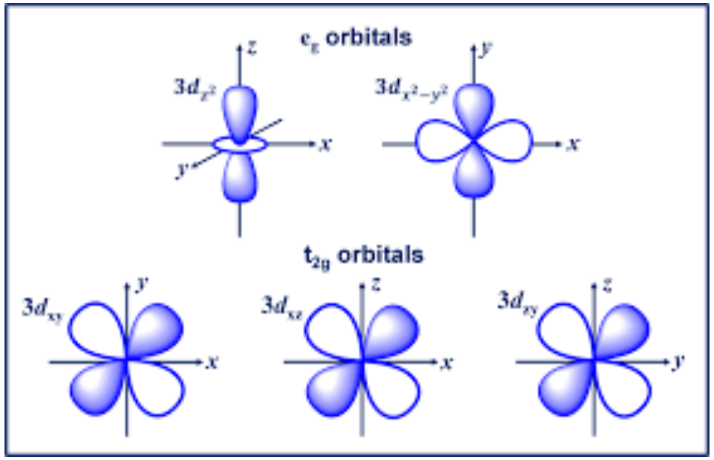
Schematics of CuO_2-plane

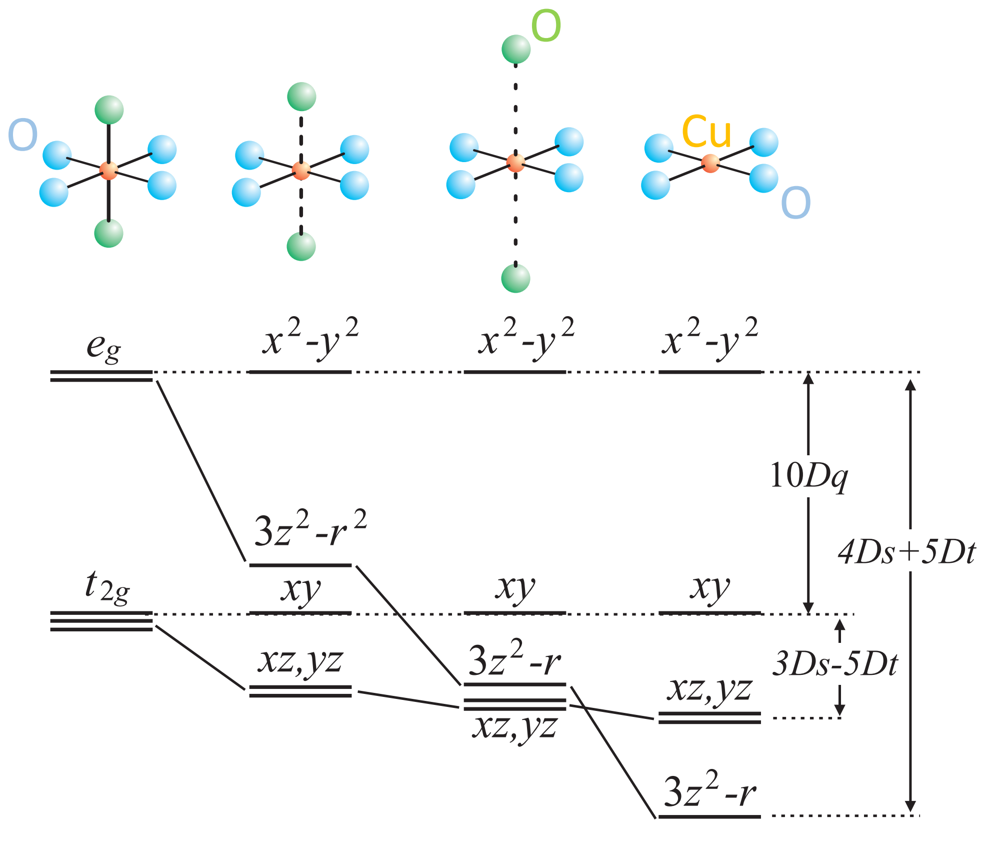


Periodic Table



Orbitals & Crystal Field Splitting

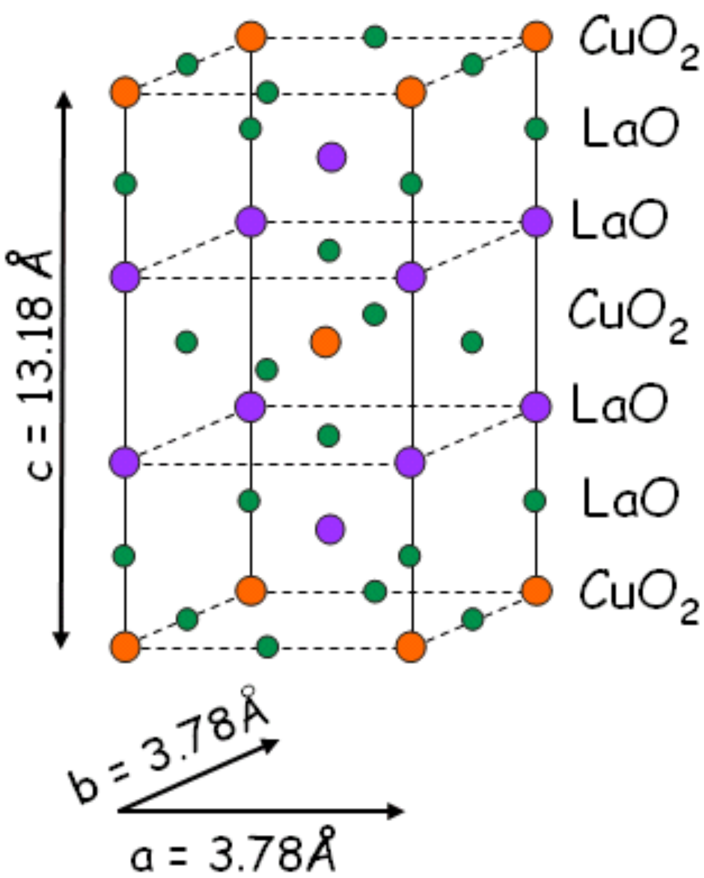


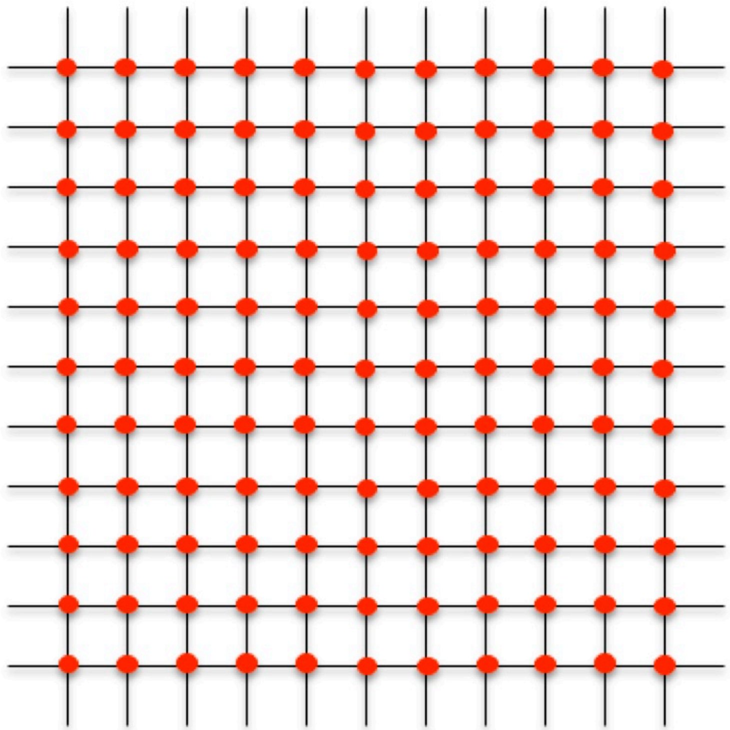


Sala et al., NJP 2011

Doping of materials

Example: $La_{2-x}Sr_xCuO_4$ Schematics of CuO_2-plane





La^{3+}

Sr^{2+}

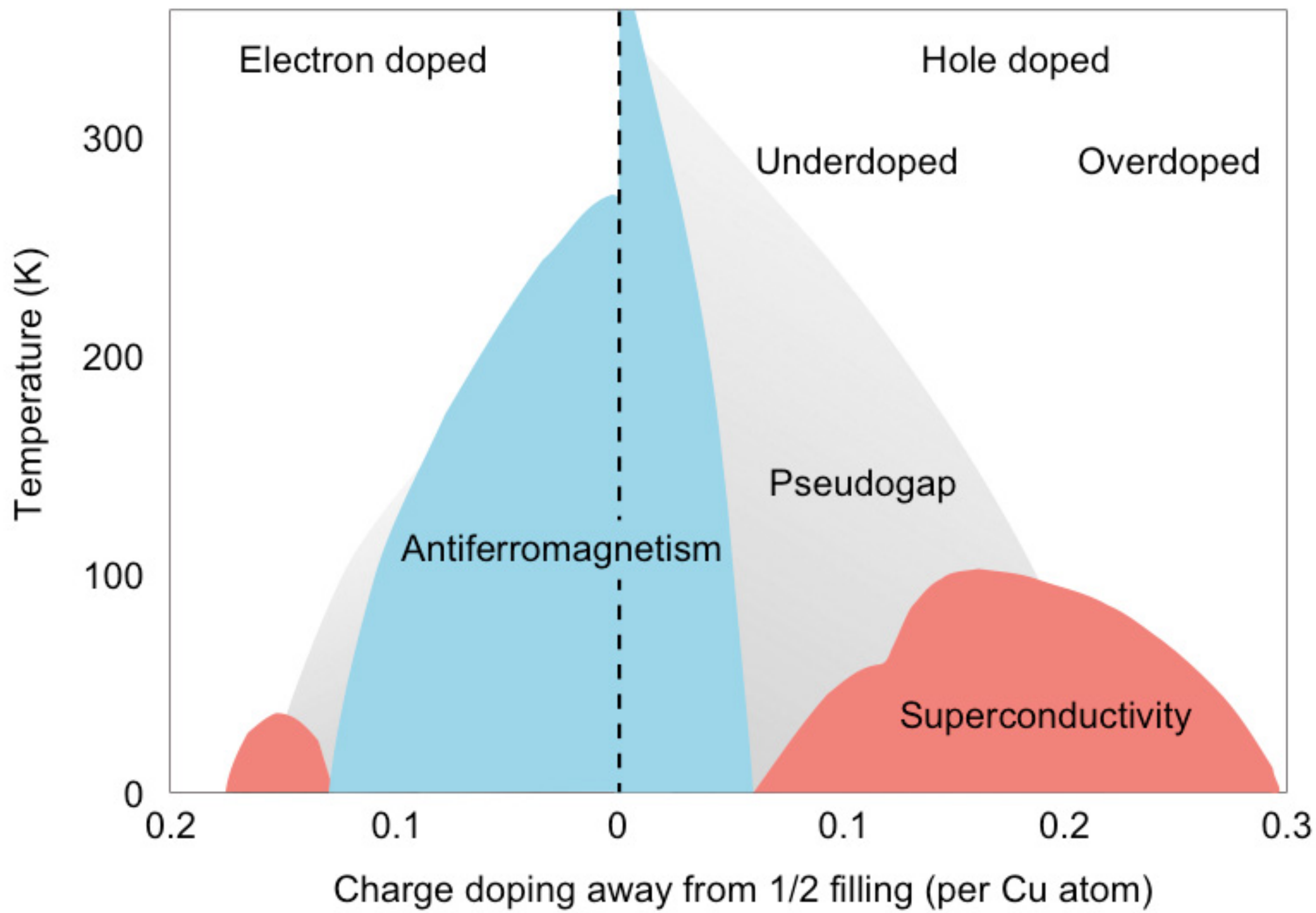
Doping of materials

K.A. Müller & G. Bednorz: Discovery of high-temperature superconductivity
Nobel Prize 1986

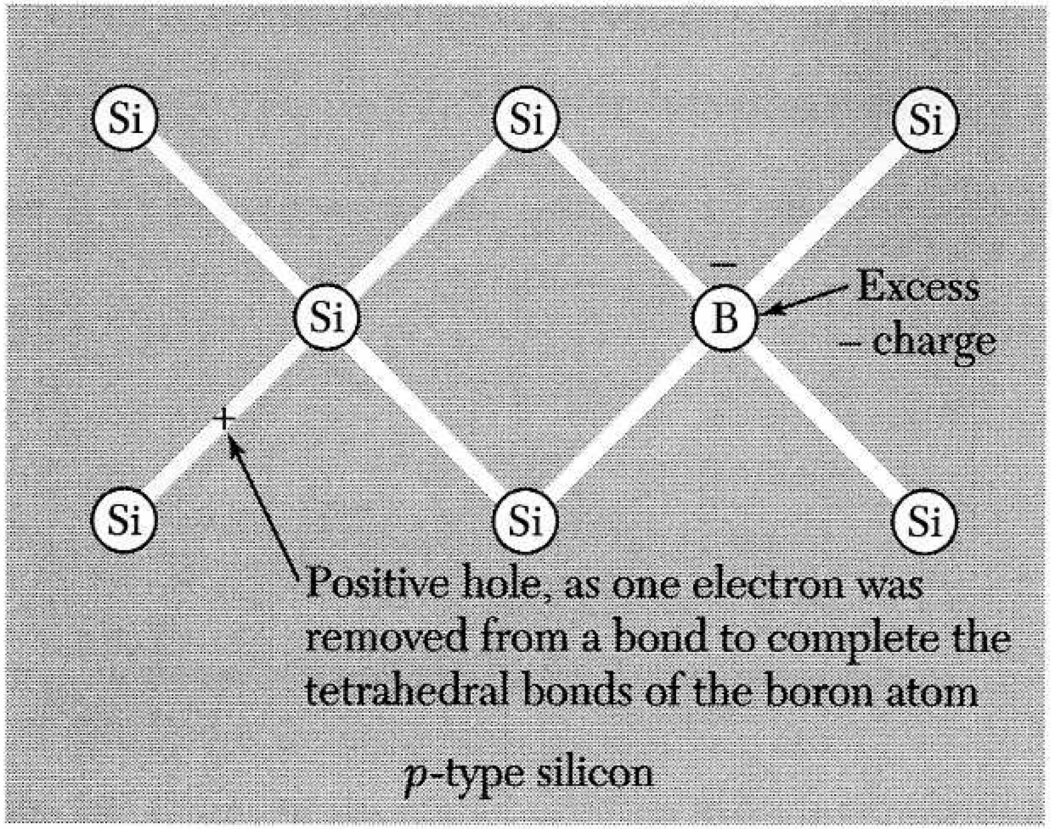
Example:
$La_{2-x}Sr_xCuO_4$
T_c =40 K

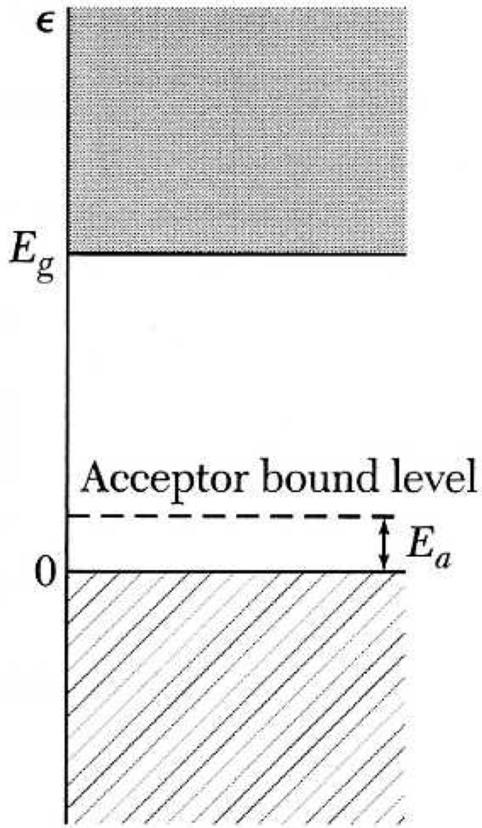
La^{3+}

Sr^{2+}



Hole - doping



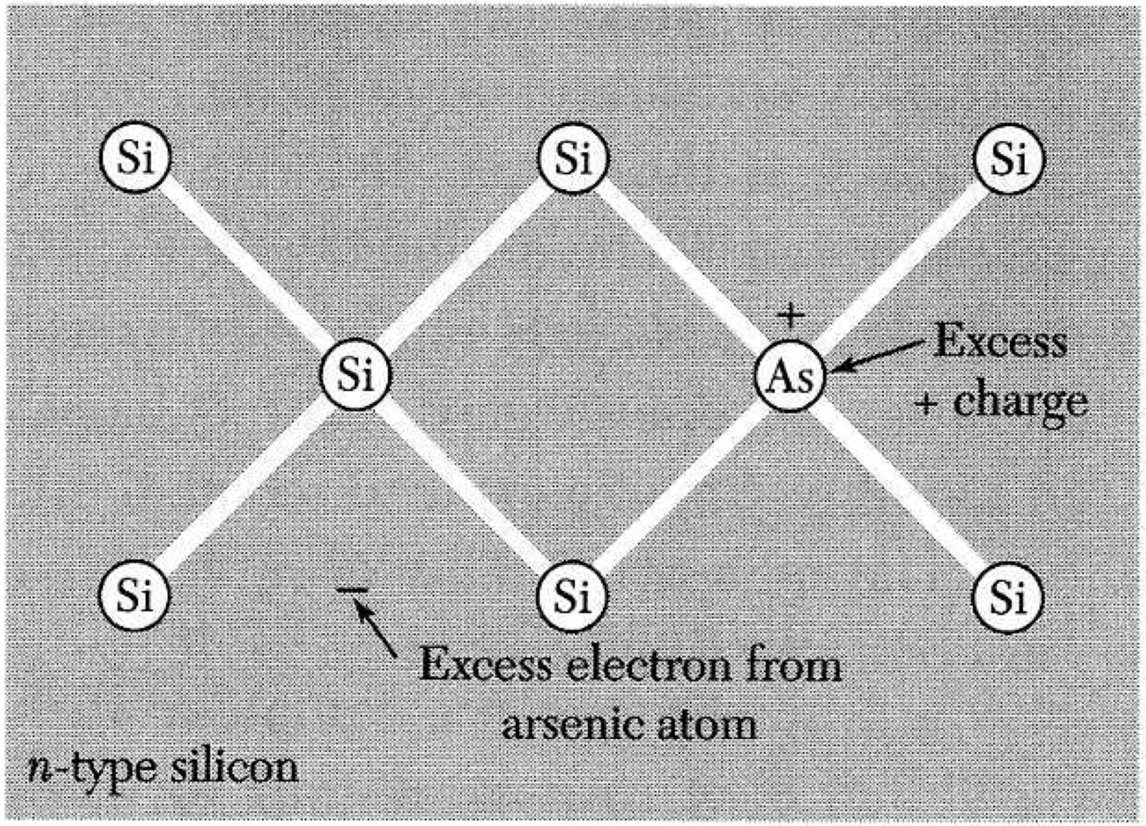


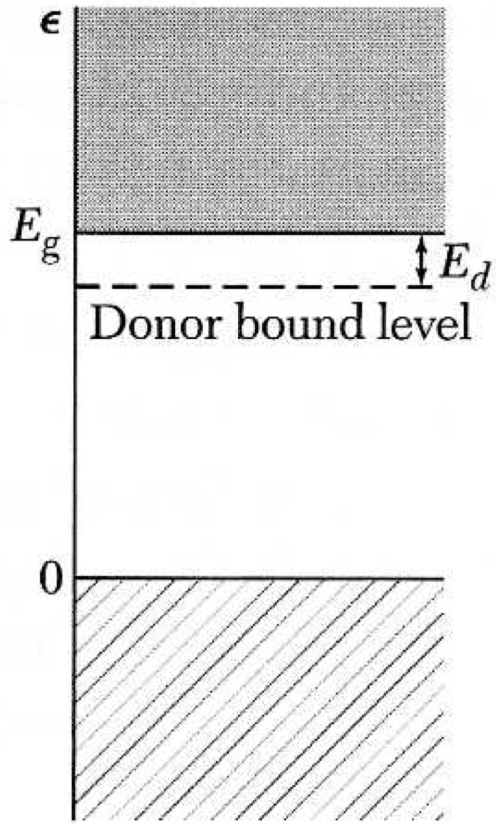
Si^{4+}

B^{3+}

From Kittel

Electron - doping



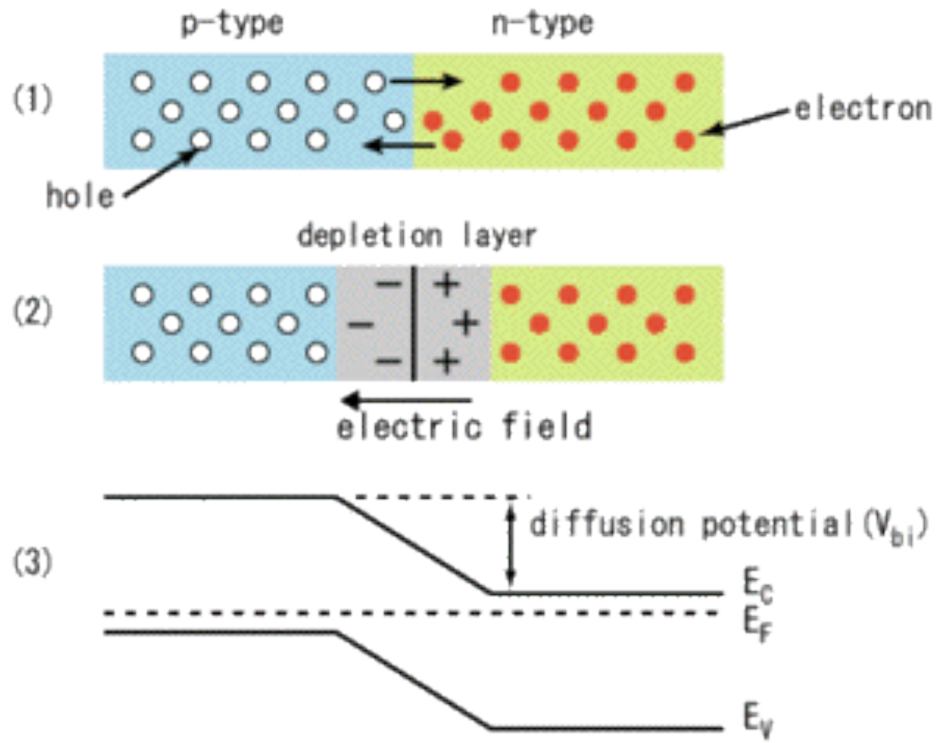


Si^{4+}

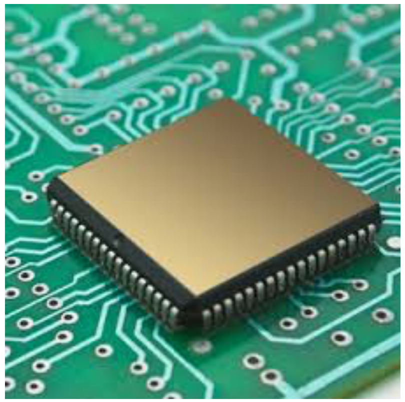
As^{5+}

From Kittel

p-n junction: solar cell



Brief – History (of materials)



Bronze- age

A bit of tin mixed with copper brought us out of the stone-age.

Iron- age

A bit of carbon mixed with iron-age gave us steel and kick-started the industrial revolution.

Silicon - age

Semiconductor doping enabled the computer chip

Today’s program

0. Summary from last week

Finished the Qauntum Oscillation Experiments

Hall effect experiment

1. Semiconductors

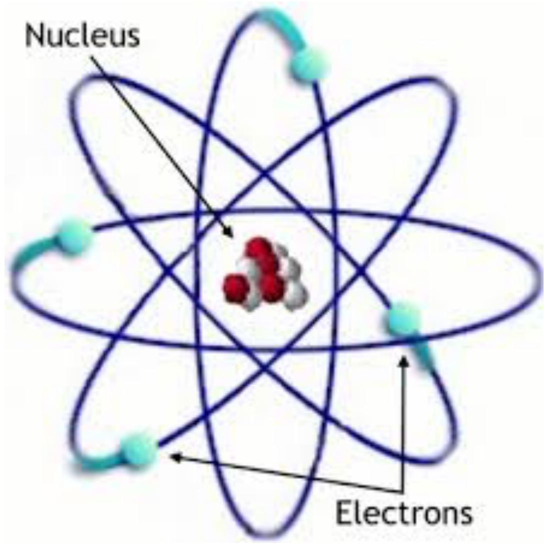
Carrier density
n- and p-type semiconductors

2. Magnetism

Ferromagnetism

Anti-ferromagnetism

The Electron

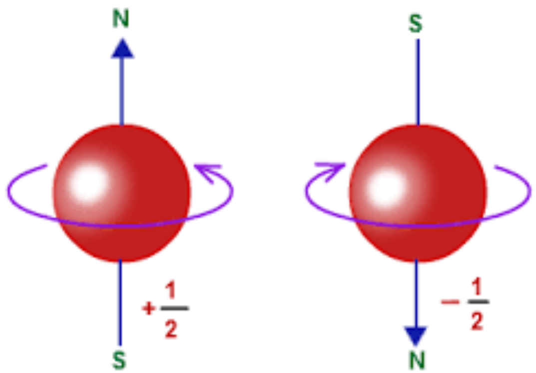


<u>Electron property</u>

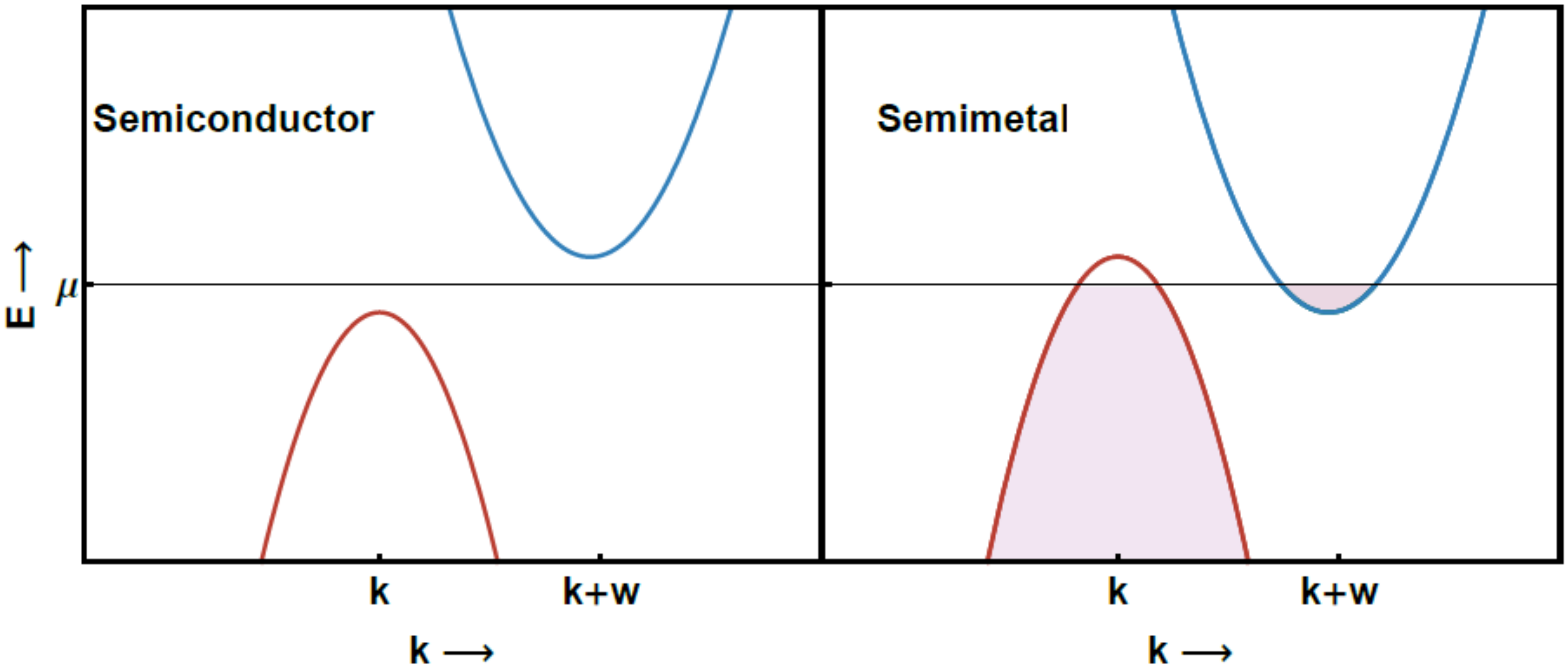
Charge

Mass

Spin



Overview



- Non Fermi surface
- Electron mobility

- Fermi surface
- Mobility

Overview

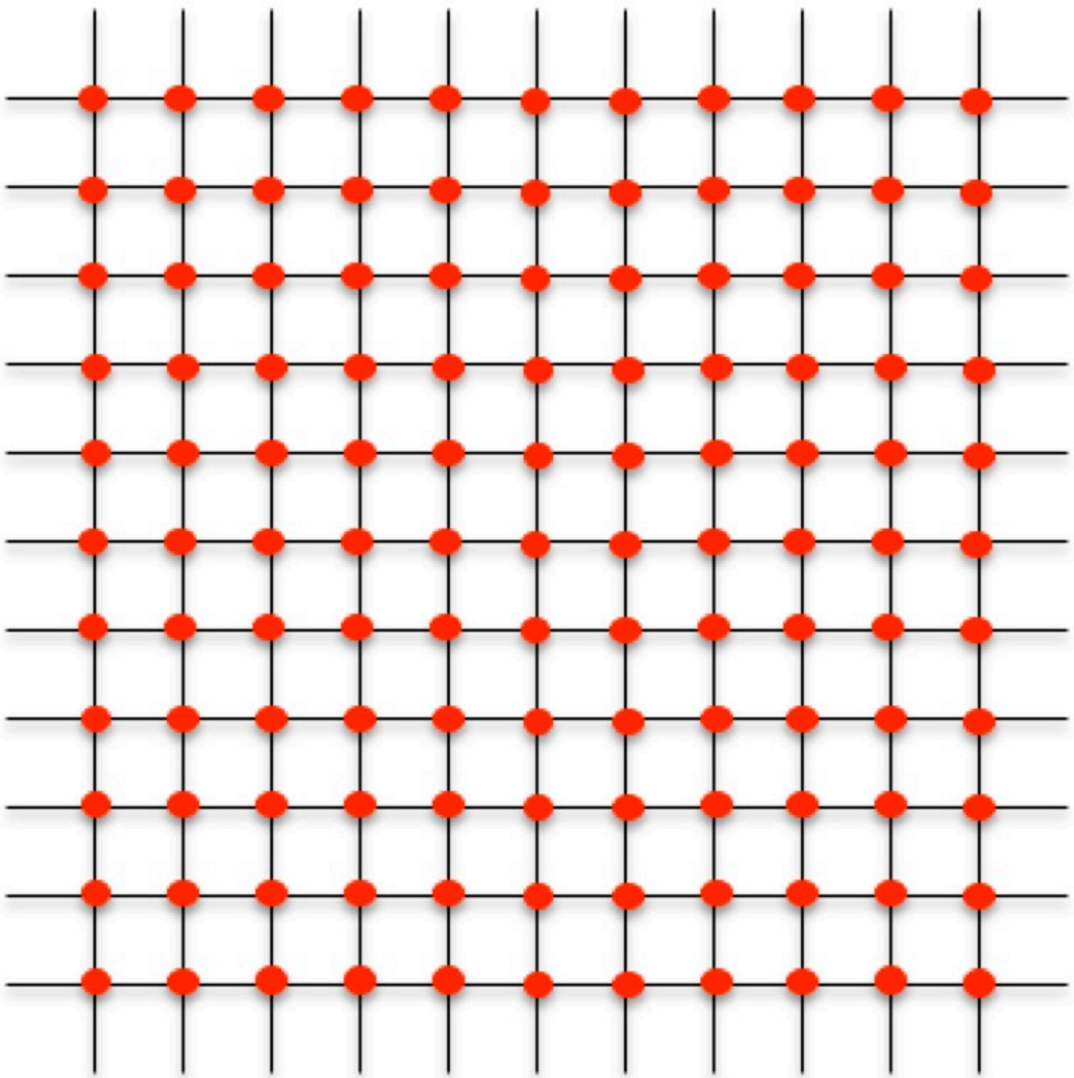
Metals

- Electrons: mobile / itinerant

Magnets

- Electrons: localized

2-dimensional square lattice



Let’s consider:

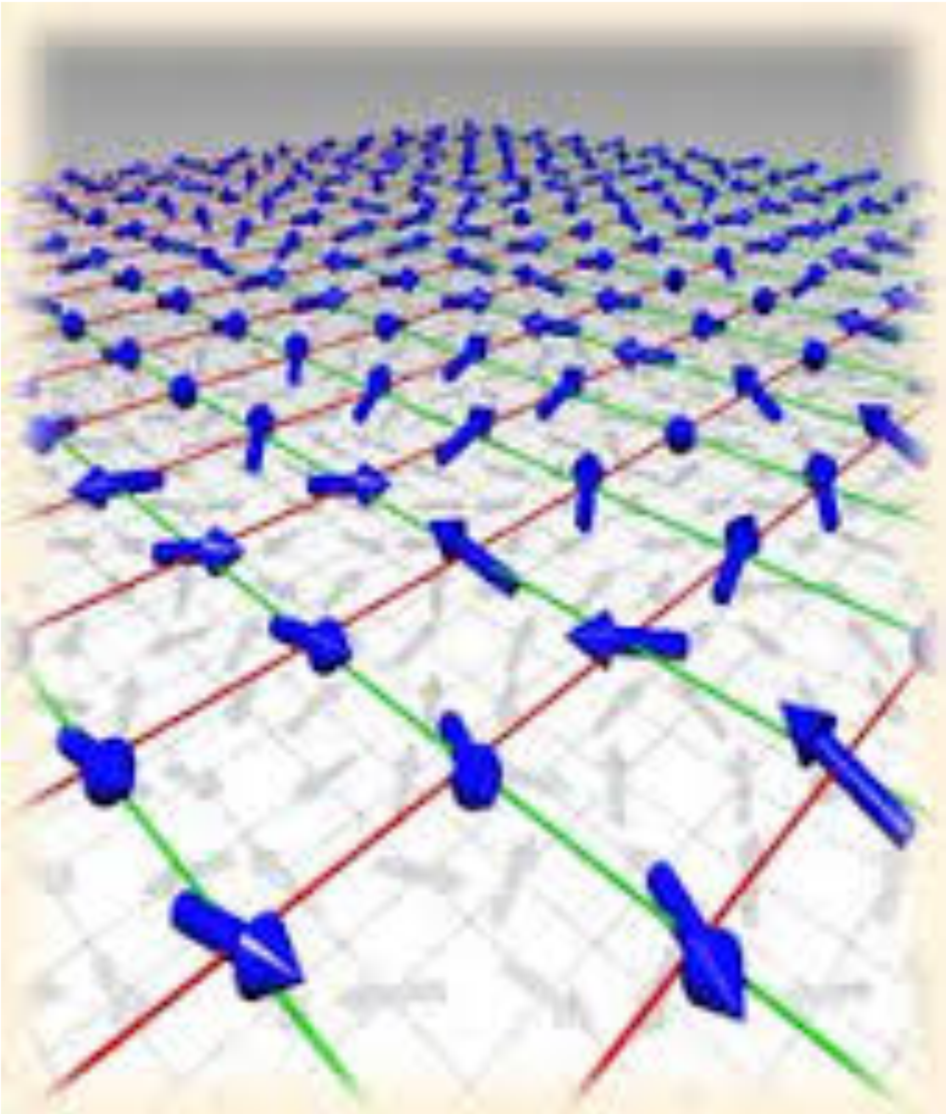
1 electron / atom

Each electron is localized

Now each red dot can represent an electron.

So, we have an electronic “crystal”

2-dimensional square lattice



Heisenberg Model

$$U = -J S_i \cdot S_j$$

Nearest Neighbor Interaction

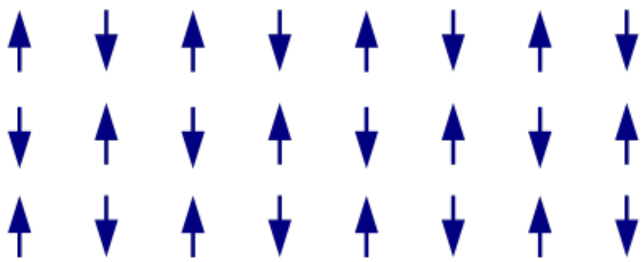
J = "Coupling between spins"

Nature likes to minimize the energy U!

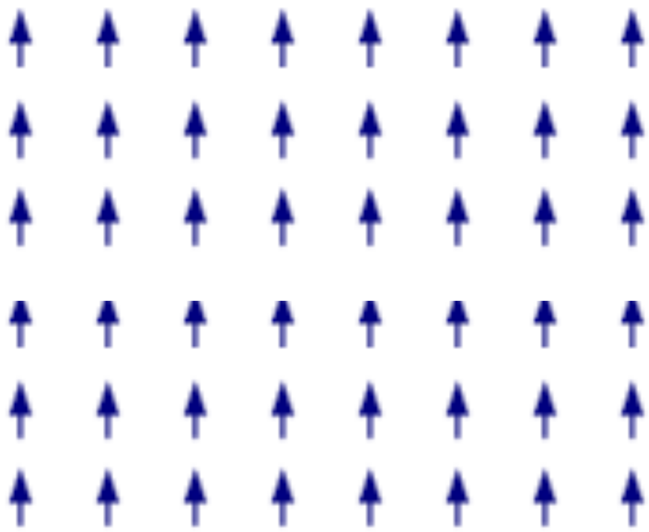
Heisenberg Model

$$U = -JS_i \cdot S_j$$

Anti-ferromagnetism
J < 0



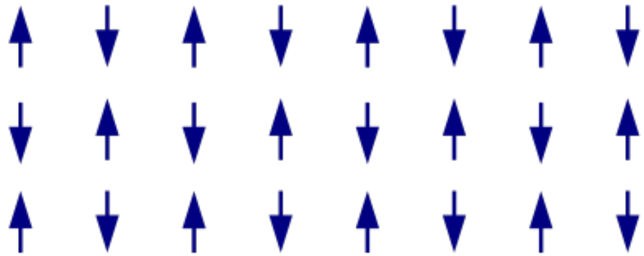
Ferromagnetism
J > 0



Heisenberg Model

$$U = -JS_i \cdot S_j$$

Anti-ferromagnetism
J < 0



1. What is the lattice parameter?

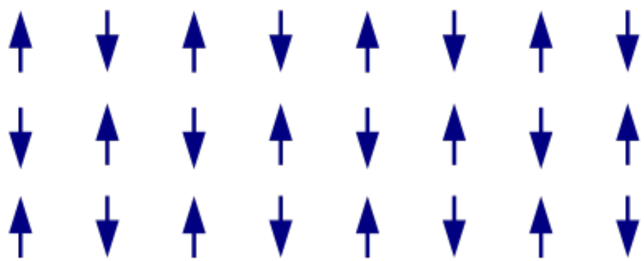
2. What happens to the unit cell?

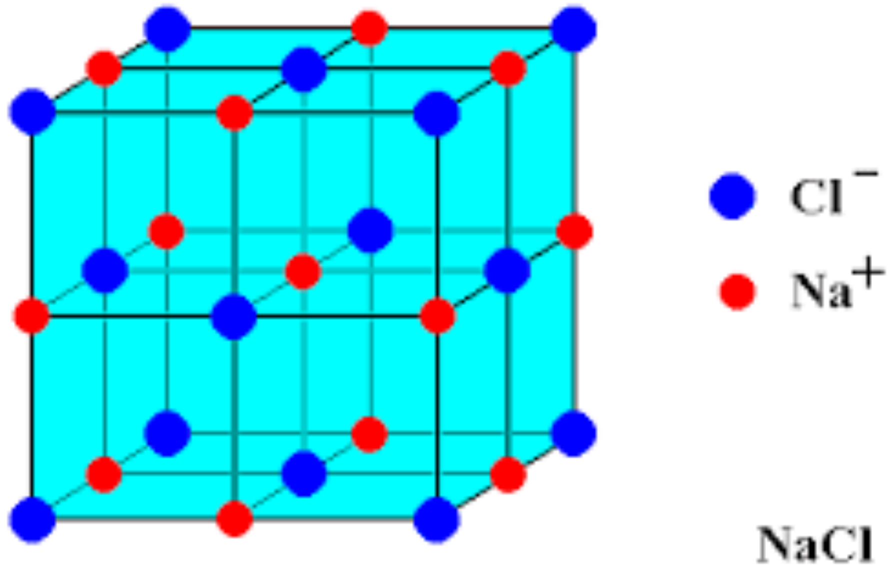
3. What about the first Brillioun zone?

Heisenberg Model

$$U = -JS_i \cdot S_j$$

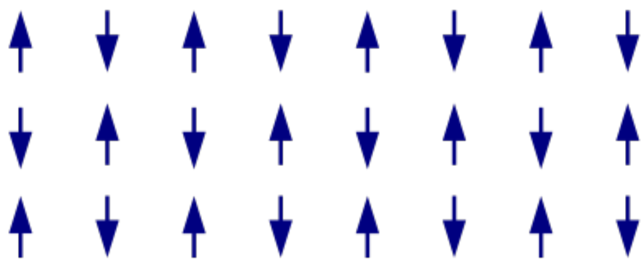
Anti-ferromagnetism
J < 0





Scattering theory: Magnetic Form Factor

Anti-ferromagnetism
J < 0



What is your expectation for the magnetic form factor?

Scattering theory: Structure Factor

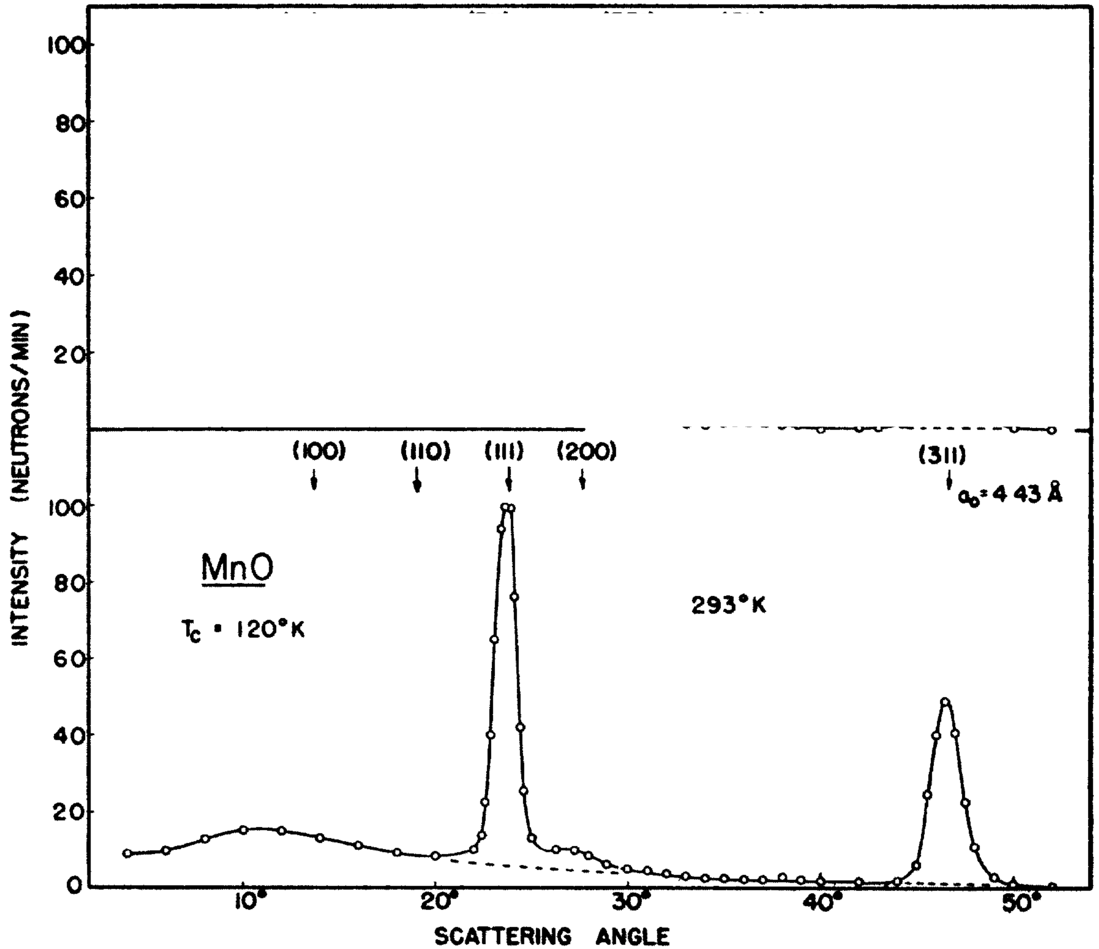


FIG. 4. Neutron diffraction patterns for MnO taken at liquid nitrogen and room temperatures. The patterns have been corrected for the various forms of extraneous, diffuse scattering mentioned in the text. Four extra antiferromagnetic reflections are to be noticed in the low temperature pattern.

Example: MnO

Atomic crystal lattice

NaCl – type structure

S = 4 (f_M - f_O) when hkl even
S = 4 (f_M + f_O) when hkl odd
S = 0 mixed parity

$f_M \sim -f_O$

Scattering theory: Structure Factor

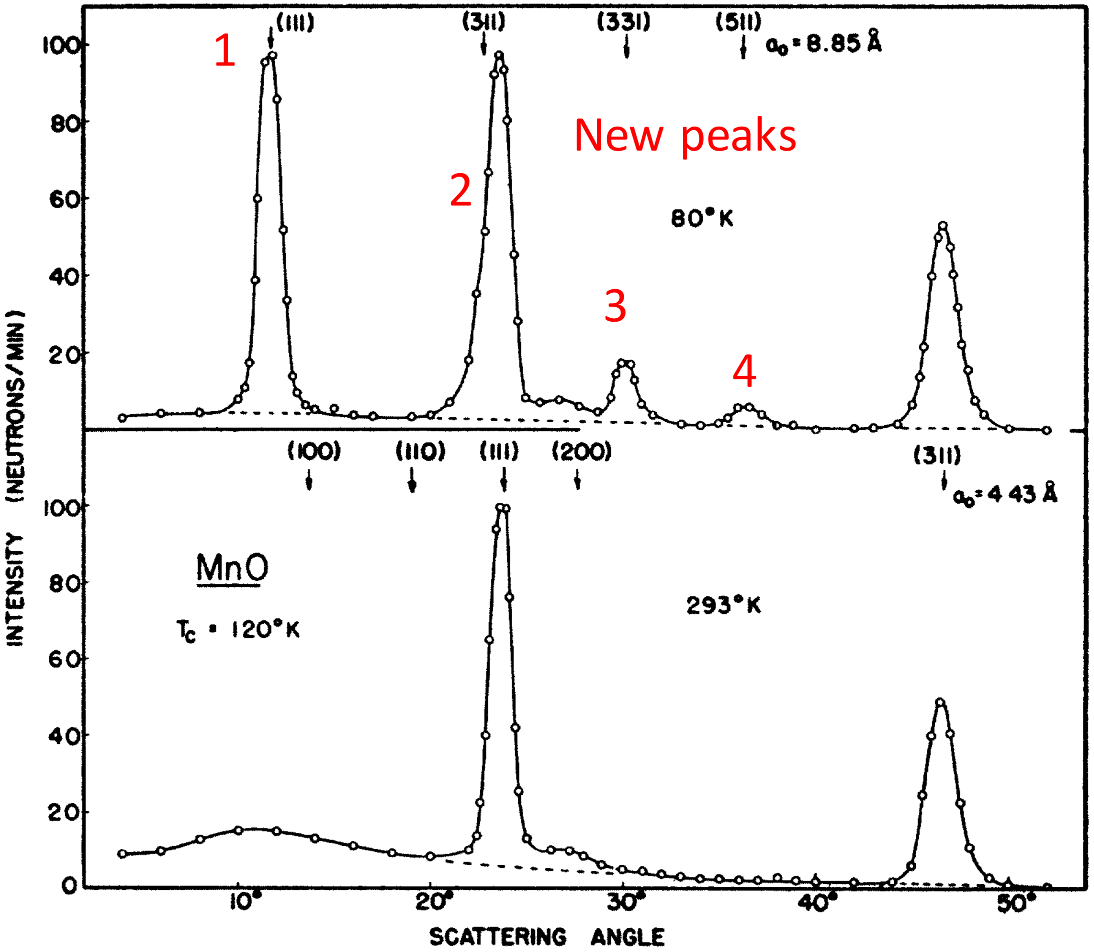


FIG. 4. Neutron diffraction patterns for MnO taken at liquid nitrogen and room temperatures. The patterns have been corrected for the various forms of extraneous, diffuse scattering mentioned in the text. Four extra antiferromagnetic reflections are to be noticed in the low temperature pattern.

Magnetic "Crystal" structure can be resolved.

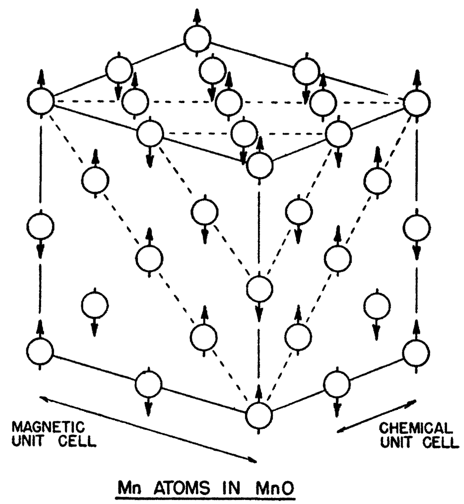


FIG. 5. Antiferromagnetic structure existing in MnO below its Curie temperature of 120°K. The magnetic unit cell has twice the linear dimensions of the chemical unit cell. Only Mn ions are shown in the diagram.

C. G. Shull *et al.*, Phys. Rev. 1951

Scattering theory: Structure Factor

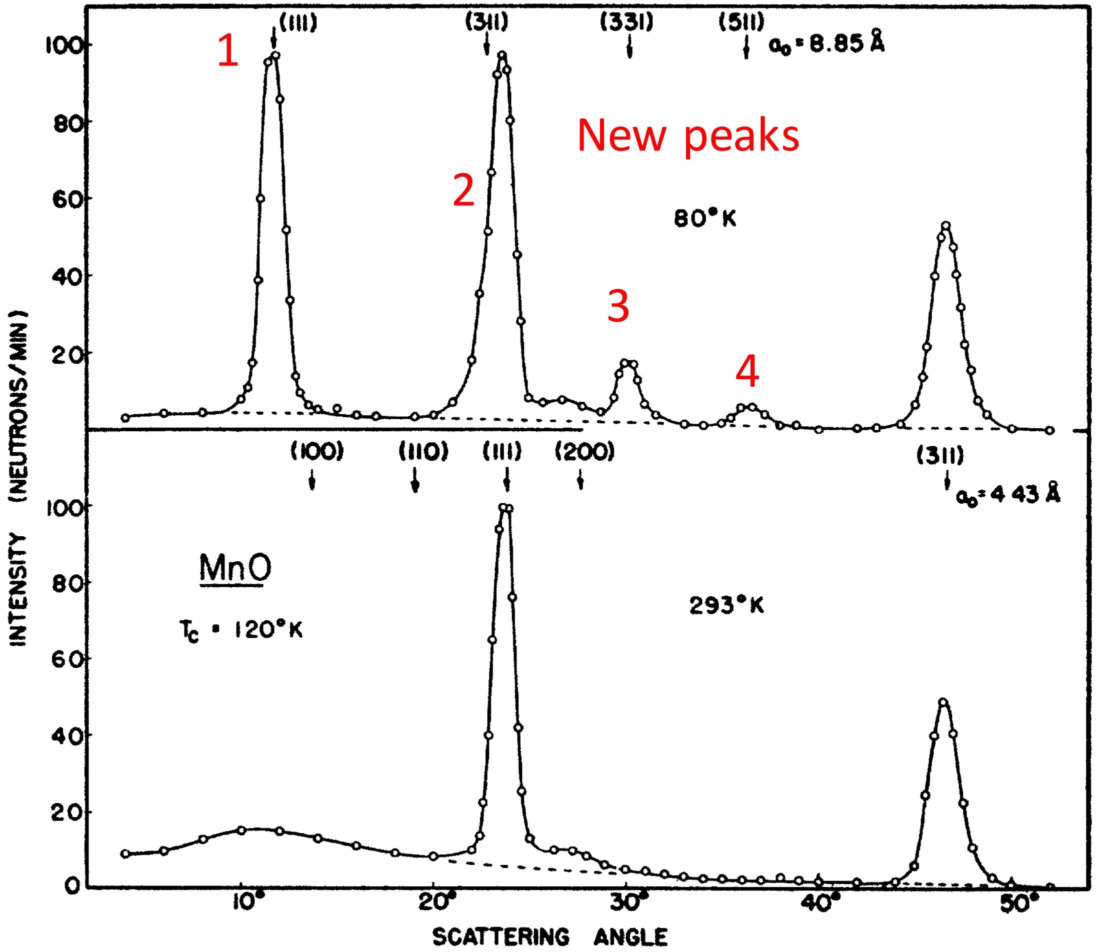
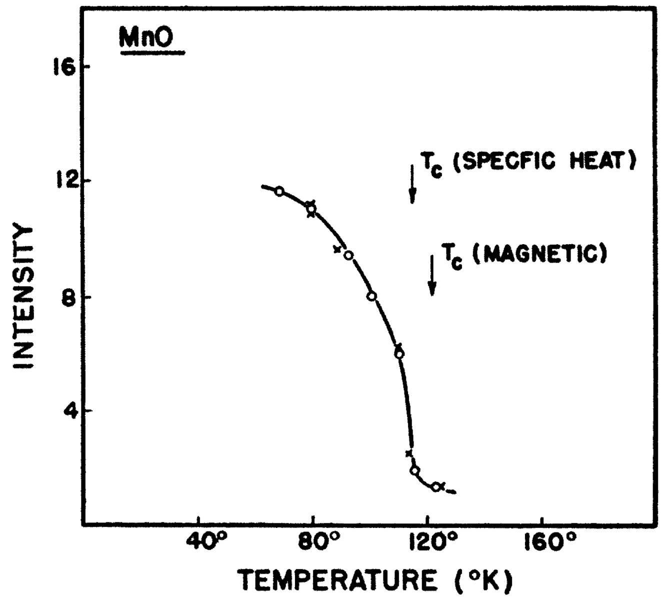


Fig. 4. Neutron diffraction patterns for MnO taken at liquid nitrogen and room temperatures. The patterns have been corrected for the various forms of extraneous, diffuse scattering mentioned in the text. Four extra antiferromagnetic reflections are to be noticed in the low temperature pattern.

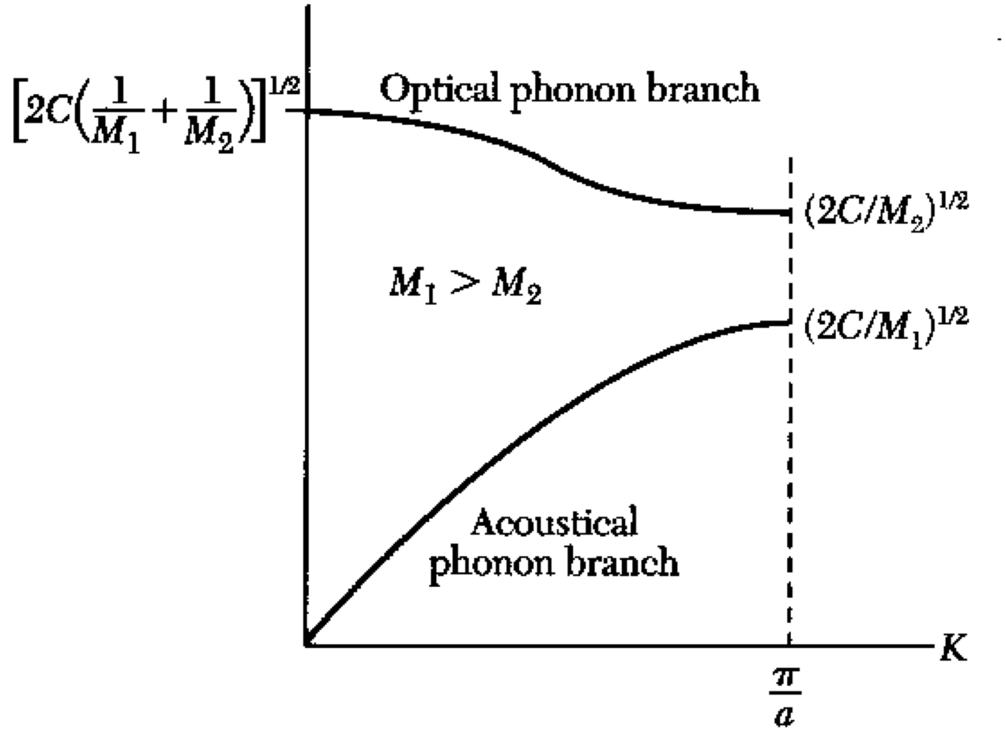
Magnetic phase transition



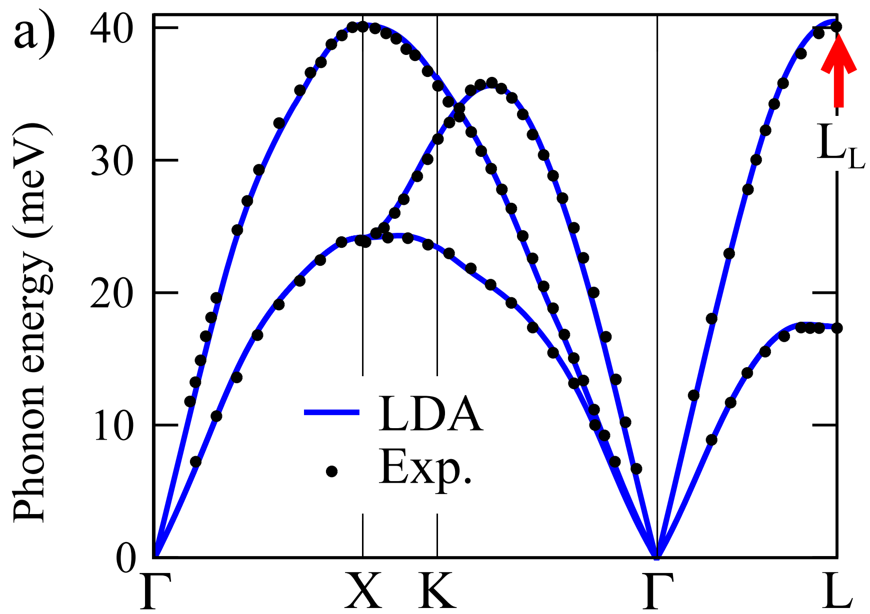
C. G. Shull *et al.*,
Phys. Rev. 1951

Phonons – Lattice vibrations

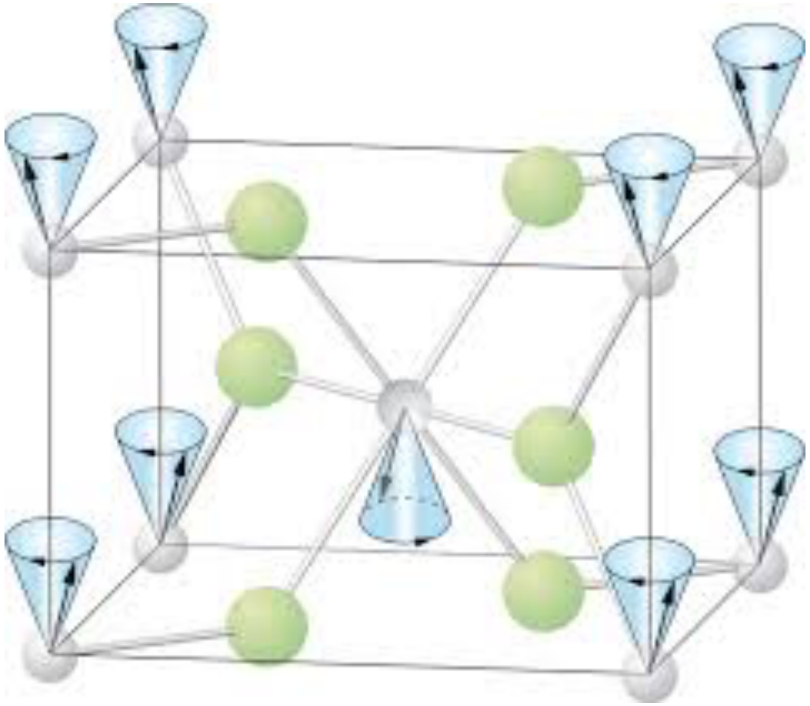
Simple Model Calculation

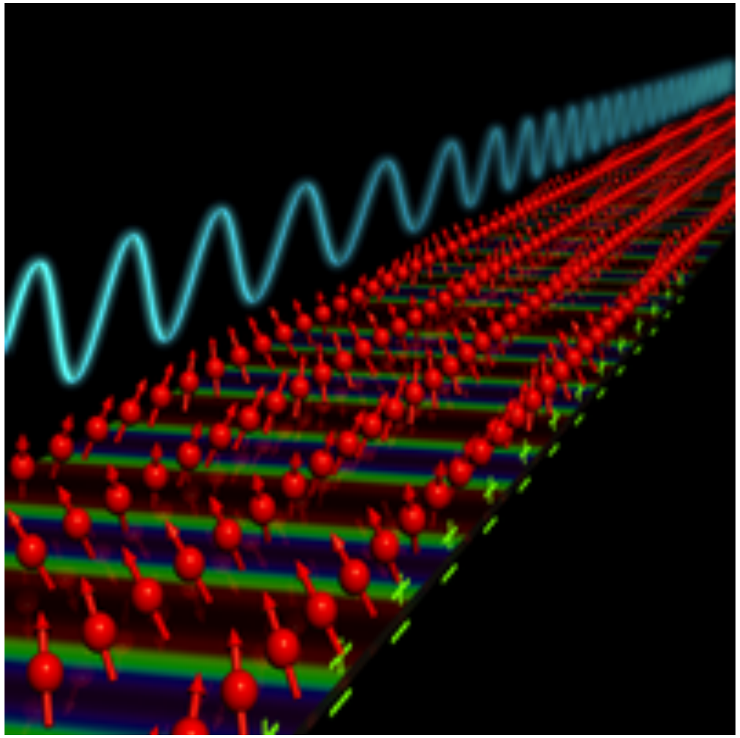


Phonons of Aluminium



Magnons – vibrations of spin





Magnons – dispersion of La_2CuO_4